



Original research article

Future energy transitions for bagasse cogeneration: Lessons from multi-level and policy innovations in Mauritius

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ABSTRACT

Agro-industries have the potential to catalyse energy access and promote development. Mauritius is one of the most advanced countries in the use of waste from sugar processing (bagasse) to simultaneously generate heat and electricity (cogeneration) to feed into the grid, but developments have evolved over several decades with complex dynamics between different actors. A multi-level perspective is used in this paper to examine this process and to extract policy lessons for other countries. The analysis shows how policies influenced the development of the bagasse cogeneration niche and changes in the sugar and energy regimes over time. The formation of independent power producers, centralisation of sugar mills, the use of a complementary fuel (coal) in the off-crop season, and targeted financial incentives were important for the development of bagasse cogeneration in Mauritius. Mauritian sugar mills are at the forefront of niche technological and organisational innovations in response to recent reduction in sugar prices. The country has been able to respond to changes and manage niche innovations strategically due to the deployment of finance, technical expertise and strong governance structures which enabled the government to coordinate with industry. Therefore, local capacity and institutional context are important for managing transitions towards sustainable energy.

1. Introduction

Agriculture plays a central role in economic development in sub-Saharan Africa and accounts for up to 50% of the GDP in some of the countries in the region [1]. Agro-industries add value to these important crops by processing them into more refined products. Agro-industries already use energy for these processes and they have access to technical expertise and finance for new energy projects. Thus, agro-industries have the potential to serve as catalysts for greater energy access in rural areas by supplying energy to employees and surrounding communities. New investments into sustainable energy in sub-Saharan Africa are set to accelerate through the Africa Renewable Energy Initiative and the African Development Bank's New Deal on Energy. The agricultural industry has the potential to achieve rapid change in energy access, modernise the agricultural sector, improve environmental sustainability and contribute to rural development. However, the willingness of agro-industries to be involved in energy supply and the barriers to their active participation in the energy sector is not well understood [2].

One of the most economically viable options for agro-industries to participate in the energy sector is the use of fibrous waste (bagasse) from the processing of sugarcane into sugar to provide heat and electricity (via cogeneration) (see Fig. 1 for an example of bagasse). The global production of sugar currently yields an estimated 565 million tonnes of bagasse per year, which is used to meet the energy requirements of the sugar mills but in most cases with surplus resource which can be used to generate additional power for sale to the grid. Such projects boost the share of renewable energy in the national generation mix, contributes to energy access and security while equally supporting climate mitigation efforts as well as sustainable development goals. The significant availability of the resource, its generation at point of use, fully-matured conversion technologies and cost competitiveness with other energy sources are thus key factors driving development of bagasse cogeneration projects.

The largest sugarcane producers, namely Brazil and India, have well established commercial-scale bagasse cogeneration plants while many other cane producing countries such as Australia, Guatemala, Kenya, Uganda, Vietnam and the Philippines are also already producing

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Fig. 1. Bagasse storage facility in Mauritius.

bagasse electricity [3]. The potential for cogeneration from bagasse has been estimated at 135,029 GWh per year globally [4] and 3885 GWh per year in Eastern and Southern Africa [5]. An analysis of five selected countries in Eastern and Southern Africa showed that there was potential to double the contribution of electricity produced from bagasse cogeneration [1].

This paper aims to identify the technical and policy success factors for cogeneration from a case study of the sugarcane industry in Mauritius, and explores the implications for the future of energy and agro-industries in Africa. This case study offers many points of reflection in the cosmopolitan energy futures in this Special Issue on ‘energy and the future’ [6] and is an important case study for several reasons. Firstly, Mauritius has been developing sugar processing systems and associated cogeneration strategies for a long time, under changing global contexts and with various national policy imperatives. Thus the experience from this single country is wide and varied. Mauritius has been ambitious and very successful in deploying bagasse cogenerated electricity, such that it accounted for 17% of the national electricity generation share in 2015 [7] with continued growing future prospects. Therefore, whilst of a single country, the scale of this case study is large. Finally, lessons learnt in Mauritius are important for other African countries not only because Mauritius is a technology use leader, but also because Mauritius is actively bringing their expertise to bear on policy innovation across multiple levels in future sugar and power projects in Africa and elsewhere. Taken together with Schelhas et al. [8], this Special Issue offers alternatives for bioenergy pathways relevant to both developed and developing countries.

The Multi-Level Perspective and Strategic Niche Management frameworks are used to trace the historical development of the sector, and examines how bagasse cogeneration contributed to the response of Mauritian sugar mills to evolving domestic and global pressures. We discuss the political, economic and policy landscape; the sugar and energy regimes; and technological developments at the niche level. The analysis focuses on the role of policy in influencing changes at the regime and niche levels. The outline for the rest of the paper is as follows. Section 2 describes the research methods and the analytical framework adopted. Section 3 presents the case study and analysis results. Section 4 discusses the implications of the case on the future of energy in sub-Saharan Africa and the energy transitions literature.

2. Methods

2.1. Research methods

Empirical fieldwork was undertaken in Mauritius in July 2015. Data were collected using semi-structured interviews, field observations, photographs taken on site and document analysis. Site visits were made to all bagasse cogeneration plants in Mauritius and their associated

sugar factories, as well as to one coal-fired power plant. Site visits were also made to field trials of new biomass varieties that were emphasized for energy production. In total, 27 interviews were conducted with a range of stakeholders, including policy-makers, sugar industry executives and engineers, project developers and researchers. The interview topics included the historical development of the sugar industry, technical details of the plants, business models, sugar industry outlook, energy policies and the experience of Mauritian sugar firms overseas. To protect the identity of participants, interviews are cited in this paper with the participant’s role in generic terms and the date of the interview (e.g. Manager 1 2015, pers. Comm. 15 July).

2.2. Analytical framework

As Hanna et al. [9] demonstrate, there has been a flourishing series of literatures with different disciplinary perspective on innovation since the 1930s. Concepts of induced innovation, the evolutionary approach and path dependency were developed in the second half of the 20th century, all highlighting the significance of existing institutions and past decisions in shaping future options. Through the 1980s and 1990s more integrated theories of innovation were developed [10]. More recently, further theoretical attention to the complexity of innovation has led to structured approaches to technological innovation as a system (e.g. [11]). A parallel set of literature explores the nature of radical and often disruptive transitions in products and services. A key component of this emerging transitions theory is the multi-level perspective (MLP) [12]. Here, energy systems can be conceptualised as socio-technical systems with actors, institutions, material artefacts and knowledge that work together to provide energy services to society. Geels explores these at the three levels of ‘micro’ technological niches, ‘meso’ socio-technical regimes and ‘macro’ landscapes. A sustainable transition involves shifting the existing socio-technical regime towards a more sustainable form through long-term, multi-dimensional and fundamental transformation processes ([13], p. 958). The transitions approach is proving valuable in improving the understanding of long-term technological change and helping inform governance and management decisions on technological change ([14], p. 1436) and has been widely adopted for analysing sustainable energy transitions in developed countries (e.g. [15,16]) and increasingly in developing countries (e.g. [17]), including by authors in this Special Issue [18,19].

This paper adopts the MLP as the framework of analysis, which organises analysis into three levels in the socio-technical system: landscapes, regimes and niches [12,20]. Central to the MLP is the socio-technical regime which represents current practices and ‘normal’ development of them [21]. The regime includes technology; user practices and markets; symbolic and cultural meaning; infrastructure; industrial networks, sectoral policy and techno-scientific knowledge. Socio-technical regimes are relatively stable configurations; transitions from one

regime to a new one take place within broader socio-technical landscapes which represent a set of deep structural trends. These include the material context of societies (e.g. the location of cities) as well as macro-economic and political trends (e.g. in commodity prices, economic growth, wars, immigration, cultural values and environmental problems). Regimes generally generate incremental changes, while radical innovations in both technologies and practices are generated in niches. Niches are circumstances which protect or insulate innovations from normal market forces and act as incubation rooms for technical innovations and networks of actors to form ([12], p. 1261).

These three levels can be seen as a nested hierarchy, where the macro-level consists of the landscape of external factors which influence technological trajectories. The meso-level of socio-technical regimes consist of stable configurations and their associated trajectories. The micro-level of niches provide opportunities for radical innovations to develop. These levels interact and co-evolve. For example, radical innovations can ‘challenge’ incumbents in the regime and move from niches into the mainstream when changes at the regime and landscape level provide a window of opportunity [12].

The pace of transition towards sustainable energy can be accelerated by planning and governance involving a wide variety of actors [22]. The MLP builds on previous work on technological innovation, and as such the ‘niches’ considered are primarily technological ones. Policy and related organisational structures are key to driving technological change, and for example Smith et al. [23] propose that policies can seek to influence transitions along two interrelated dimensions

- Policies which seek to change the selection pressures on the regime (e.g. regulatory and fiscal policies), and
- Policies which affect the coordination of resources available to adapt to these pressures (e.g. innovation policies).

But the MLP does not lend itself well to exploring processes of innovation in policy *per se*. Reflecting the importance of policy, Strategic Niche Management (SNM) has been developed to explore and guide the contributions of policy to support technological innovation and stimulate transitions. SNM is “the creation, development and controlled phase-out of protected spaces for the development and use of promising technologies by means of experimentation, with the aim of (1) learning about the desirability of the new technology and (2) enhancing the further development and the rate of application of the new technology” [20]. The SNM framework has been applied to a diverse set of case studies in sustainable innovations, including in the energy sector [24]. In this Special Issue, Schaube et al. [19] use SNM and MLP to analyse the development of the renewable energy niche in Argentina. These applications of the SNM highlighted that successful development of a technological niche depends upon the articulation of a vision, building of social networks and learning processes at multiple dimensions [25].

SNM is about more than just technology policy and is “aimed at making institutional connections and adaptations, at stimulating learning processes necessary for further development and use of the new technology” [20]. An integrated set of policies is needed to address the economic, technical, social or institutional barriers to the use and diffusion of the new technology [20].

However, in presenting a useful overview of the progression from technological niche through protected market niche and on to full market, Raven [26] argues that SNM takes an overly simplistic view as progression from one level through the rest is rarely linear. Kivimaa and Kern [27] argue that in addition to SNM’s focus on niches, innovation in policy approaches and instruments has an important role in accelerating the destabilisation of the existing regime, for example by substantially changing economic conditions that affect the relative performance of the niche and regime technologies. Newell et al. [28] argue that transition to sustainable energy is a complex socio-political process manifested in multi-actor networks that go beyond formal hierarchies. Ratinen and Lund [29] argue that for radical innovations to lead to broad sociotechnical change requires a high degree of inclusion in the policy process and outcomes. Analysis of sustainable energy transitions in other developing countries show that this will require coordination between government and industry [30,31]. Therefore, alongside the MLP this paper uses a broader approach to examining innovations in policy and the surrounding institutional contexts, directed at both niches and regime change.

We use the case of Mauritius to explore the parallel technological, institutional and policy developments in the transition from fossil to biomass-fuelled economy, based on the MLP and policy innovation. The interviews, site visits and documentary analysis undertaken for this paper have been used to build understanding of the Mauritian energy situation through the lens of the MLP framework and related policies, allowing consideration of future prospects for cogeneration technologies and of policy priorities, guided by this structured understanding of the socio-technical system in place.

3. Results & analysis

As a small island developing state without fossil energy resources, Mauritius depended almost entirely on imported fuel oil for power generation before the 1990’s. This dependence was subject to price escalation and volatility, and supply disruption during the international oil crises. A drive to improve energy security through diversification, as well as ambitions for sustainable development, drew attention to exploitation of local resources. Bagasse-derived electricity was seen as a good solution given the cross-sectoral benefits to both the agricultural and energy sectors. Simultaneously, much policy attention was given to the preservation of the sugar sector, given its socio-economic, cultural and political importance.

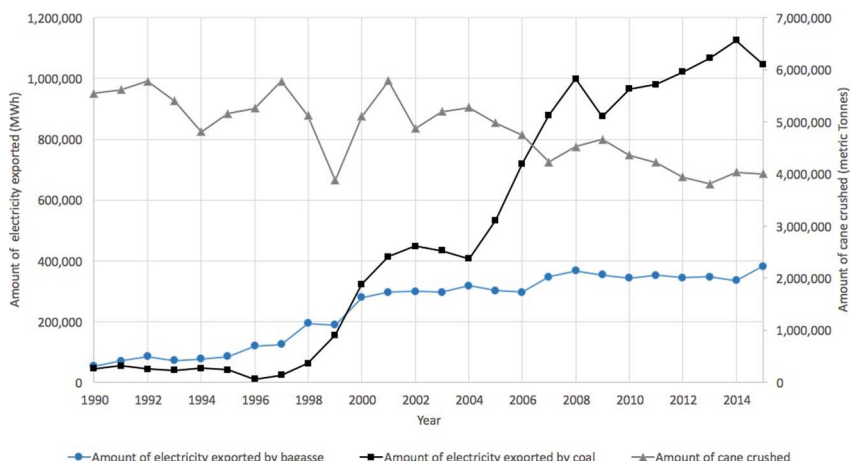


Fig. 2. Electricity exported to national grid from bagasse and coal 1990–2015 in Mauritius. Constructed by authors from [47,7] MSIRI, 1990–2015 and CSO, 1990–2015.

Fig. 2 shows the evolution of electricity produced from coal and bagasse over the past two and a half decades in Mauritius. It shows an initial slow growth period for cogeneration when much of the policy and technical groundwork was laid (1980–1990), and then a period of accelerated growth (1991–2008), followed by stable electricity production (2009–present). During the same period, coal based electricity has grown substantially: it is used as a complementary fuel in the cogeneration plants during off-crop season (around 6 months). However, there is a current need to curb the increasing amount of coal used due to environmental constraints.

This section traces the development of grid-connected bagasse cogeneration in Mauritius by mapping it to the MLP and discussing policy innovations and their influence at the regime and niche levels. We discuss the national and global social, economic and institutional influences at the landscape level; the sugar and energy regimes; and the development of grid-connected sugarcane bagasse cogeneration at the niche-level. Importantly for the international significance of this case, Mauritius has been pursuing diversification from sugar as the single output of the sugarcane industry, and substitution for fossil-fuelled power generation for several decades, through multiples sets of domestic and global circumstance. As such we explore the case across a series of time periods following the development and adoption of technologies which allowed the sale of electricity from bagasse cogeneration to move from niche innovations to being part of the regime.

3.1. Historical foundations of the sugar industry and energy supply

Mauritius has had a long history of cultivating sugarcane and has deep cultural and social ties to this crop. The Dutch East India Company first introduced sugarcane cultivation in 1639 using slave labour (1638–1710). However, the production of sugar on a significant scale was only developed under French rule (1721–1810) with African slaves. By 1755, enough sugar was being produced to meet the needs of the inhabitants of the island as well as for its neighbouring Reunion Island. When the British took over the island in 1810, they realised the economic importance of sugar and a new impetus was given to sugarcane development. By 1825, 10,975 ha of land were under cane cultivation and 10,800 t of sugar were produced in 106 mills [32]. Slave labour was abolished in 1835 and indentured workers were brought in from India. By the 1860's Mauritius was the leading sugar cane producer in the British Empire [33]. The highest number of sugar factories ever in the island was 259 in 1858 with a sugarcane crop cultivation area of 46,430 ha [32].

Sugar production was initially under the control of Franco-Mauritians. When world sugar prices declined in the second half of the 19th century, sugar estates consolidated their lands or sold small parcels of land to Indo-Mauritians. By the early 20th century, Franco-Mauritians owned two-thirds of the sugar cane fields and Indo-Mauritian small planters owned about one-third (usually less than 4 ha each) ([34], p. 165). Bagasse has been used to meet the energy needs of sugar mills since the early 19th century. However, factories were small in scale, and designed to get rid of bagasse waste and so had relatively low energy efficiency [35].

In terms of electricity supply, like many small island developing states, Mauritius was heavily reliant on fuel oil for electricity generation. Prior to 1952, electricity was supplied by small private power producers directly to consumers. The national Central Electricity Board (CEB) was created as the sole electricity utility in 1952, reporting to the Ministry of Energy and Public Utilities, to generate, transmit and distribute electricity on the island. The establishment of the CEB subsequently created the enabling environment for sugar factories to participate as power generators in the electricity system. In 1957, one sugar factory (St Antoine) became the first independent power producer to sell electricity to the grid. 'Intermittent' electricity was sold to the national grid, that is, any surplus from the power generated on the site after meeting the requirements of the sugar production process [36].

3.2. Phase 1: laying the groundwork (1980–1990)

3.2.1. Landscape level

The heavy reliance on fuel oil left the country vulnerable to increases in oil prices during the oil crises in the 1970's and early 1980's. This landscape pressure motivated the Government to seek greater diversity in fuel for electricity generation to improve energy security. Continuing downward pressure on global sugar prices was similarly influential on the Government, which sought alternative markets for sugar of different grades, and for by-products of the industry.

3.2.2. Regime level

By the early 1970's, 21 sugar factories were selling a total of 25 GWh (or 16% of total electricity demand) to the national grid at an average price of 0.6 US cents per kWh [36]. However, the inconsistent supply and low price of electricity were not conducive to heavy investment in modern and efficient cogeneration technology and the percentage that bagasse cogeneration contributed to the grid began to shrink. Thus, electricity supply remained closely tied to imported fossil oil, burnt in large thermal power plant owned by the CEB, and distributed by them. There was limited contribution to electricity supply by independent power producers at the time (Researcher 11 2015, pers. comm., 27 July).

3.2.3. Niche level technical innovation and changing policies

Reflecting the constraints on expanding bagasse-fuelled electricity supply imposed by the intermittency issues, technical solutions were explored. In order to better modulate the supply of electricity between the sugar industry and the utility company, the concept of a 'continuous' power supply for a specified period was developed whereby a fixed amount of electricity, as agreed in a Power Purchase Agreement (PPA), was to be sold by the sugar factories during the cane crushing season only. In 1980, a sugar mill entered into the first continuous PPA with the CEB to supply 6 MW to the grid during cane crushing season only [36]. However greater value would be attached for power supplied year-round; this was pursued through technology for flexible fuelling. Cogeneration management companies which operated internationally helped to share technology; a trial was run first on the neighbouring Reunion Island, and then Mauritius installed its first firm power plant (21.7 MW) in 1982, which exported power all year by burning bagasse during the cane crushing season and coal during the rest of the year [36].

An alternative concept for year-round generation of electricity was the storage of bagasse through drying and compressing into pellets. In 1985, a full-scale pelletisation plant designed to produce 14,000 t of pellets per annum was constructed. However, the plant produced only 4395 t of pellets in 1986 and closed down in 1987 as technical constraints made the plant financially unviable at that time [37]. As above, the sugar companies were keen to innovate, for both commercial gain and to address national energy needs. But the technical opportunities required policy and institutional change if they were to succeed at scale.

Two major policies were implemented at this time to encourage the development of bagasse cogeneration – the Sugar Sector Action Plan (SSAP) and the Sugar Industry Efficiency Act.

In 1985, the government prepared the SSAP [67] in consultation with the private sector. This plan aimed to modernise cane agricultural production in fields and improve productivity in sugar factories. The proposed bagasse energy incentives were aimed at improving energy efficiency in factory processes to enable a higher amounts of electricity to be sold to the national grid, incentivising bagasse storage, and creating independent power companies that separated the cogeneration power plant from the sugar mill [36], allowing it greater operational flexibility and to secure bagasse from more than one sugar mill.

Several fiscal incentives were provided in the Sugar Industry Efficiency Act in 1988 to further promote bagasse cogeneration. Supporting the innovations for flexible fuelling, sugar factories were

given reductions on the duty they paid for the sale of bagasse to cogeneration plants involved in the generation of firm power (a “firm power plant” is a power plant that can be dispatched as required, as it is not reliant on intermittent resources). Income tax exemption of 75% was also allowed for the sales of bagasse by sugar factories to other sugar factories producing firm electricity. There were many relatively small to medium sized sugar factories at that period which could not individually produce the critical amount of bagasse needed on a single site to ensure the economic viability of a cogeneration plant. The two proposed measures were thus aimed at ensuring that adequate bagasse was supplied to the power plants. The power plant benefited from an income tax exemption for 60% of the income generated from the sale of electricity to the national grid. The low price of intermittent power was maintained given that this mode of power supply was found to be highly inefficient and did not match the national electricity load requirements. To enable better energy savings on the processing side and safeguard the environment, the initial tax exemption allowance for more efficient machinery or fly ash treatment plants was increased from 50% to 80% [36].

3.2.4. MLP analysis of Phase 1

Under Landscape pressures of high and volatile fossil fuel prices and development-led growth in power demand, this phase saw technical experimentation in bagasse – derived fuels, in cogeneration technology and operating practices. Some successes with commercial-scale operations led to the establishment of enhanced multi-fuel cogeneration as a viable option for providing power to the grid. The government closely supported this process through policy and regulatory changes, and ‘firm’ power from bagasse/coal generation entered into the Regime. Previous studies of SNM have shown that clear articulation of the vision underpinning policy formulation is one of the keys to the successful development of technological niches. A key regulatory change which supported the development of the niche in Mauritius was the creation of independent power companies, not directly owned by the sugar companies; this development represented a major challenge to the regime, introducing direct competition to the incumbent (largely oil-fired) power producers. Here, policies were used to actively destabilise the existing regime (as discussed by Kivimaa and Kern [27]). During Phase 1, the desirability of coal as the preferred off-season fuel was established (as bagasse pelletisation had failed at this time) and the policy support mechanisms set the stage for scaling up during the next phase.

3.3. Phase 2: scaling up (1991–2008)

3.3.1. Landscape level

The concerns over the dependence on fossil fuels, and the need to make savings on foreign exchange by decreasing the importation of petroleum products deepened during this period (Researcher 11 2015, pers. comm. 27 July). The Earth Summit in Rio in 1992 galvanised international action on sustainable development and opened up new forms of financing for clean energy projects.

Mauritius expected to be severely affected by a fall in the price paid for its sugar. Global sugar production and trade was highly regulated by tariffs, quotas and multilateral agreements from the beginning. The most important arrangement for Mauritius in recent years had been the European Union’s (EU) sugar regime, designed to protect EU sugar beet growers using guaranteed high internal prices, production quotas for each member state, tariffs on sugar imports and export subsidies. A group of former colonies in Africa, Caribbean and Pacific (APC) regions, including Mauritius, received preferential terms for sugar export to the EU since 1975. Under the EU’s Sugar Protocol, the EU could buy a fixed quantity of sugar from APC producers at its internal price [38]. The EU moved to reform its sugar regime due to a ruling by the World Trade Organisation: the first round of reforms in 2006 reduced the price of sugar in the EU by 36% over four years, which meant reduced revenues for Mauritian sugar producers [39].

3.3.2. Regime level

In the previous period the concept of the ‘firm’ power plant burning bagasse and coal, supported by ongoing process and organisational improvements in the sugar industry to maximise the amount of bagasse-derived electricity for export, had been established and entered the Mauritian power sector and sugar sector regimes. Through the 1990s and early 2000s a great deal of technical improvement and investment took place (eg in high pressure boilers, for greater power generation efficiency) and reorganisation of sugar factories (eg to capture economies of scale), but arguably these represent the ‘normal’ development of current practices [21] within the regime, and thus incremental rather than radical innovation.

The most important policy for scaling up bagasse cogeneration during this period was the Bagasse Energy Development Programme (BEDP) which was established by the Government in 1991 with the assistance of the World Bank in consultation with the private sector, the public sector, and government agencies. The BEDP aimed to fulfil multiple objectives: to displace the substantial investments in fuel oil plants to be effected by the national utility company of the country; to reduce the dependence of the country on fuel oil products; to broaden the electricity supply mix; to rehabilitate and modernise the sugar industry to improve its competitiveness; to make savings in foreign exchange by decreasing the importation of fuel oils; and to contribute to greenhouse gas mitigation efforts by displacing fossil fuels [40].

The BEDP recommended the construction of two firm power plants (operating at 60 bar boiler pressure) annexed to sugar factories. The firm power plants would maximise electricity production from bagasse during the on-crop season (around 6 months) and use coal as a fuel in the same boiler during the off-crop season to ensure year-round production of electricity. The existing power plants would be rehabilitated to move from intermittent to continuous supply of electricity during the cane crushing season. Satellite sugar mills were to burn bagasse to meet their own energy needs and sell any excess bagasse to a neighbouring power plant. Use of coal during the off-crop period was expected to diversify the electricity production mix of the island away from heavy fuel oil and diesel. Coal was readily and cheaply available from supplying countries (notably South Africa), less exposed to political risks and instability. However, it was suggested to investigate the possibility of compacting bagasse for sales between factories and the use of cane tops and leaves and trash as a complementary boiler fuel to reduce reliance on coal. The BEDP also addressed the issue of capacity development in the sugar industry [36].

Funding for the implementation of the BEDP was secured by the Government through the Sugar Energy Development Project loan amounting to US \$15 million. The Global Environment Facility provided an additional US \$3.3 million grant to undertake projects in connection to the BEDP [36]. However, the implementation of plan was limited and 60% of the Sugar Energy Development Project loan remained untapped. This was due to difficulties in reaching agreement on electricity and bagasse pricing, and difficulties in reaching viable economies of scale. Adjustments were made to implementation strategy of the BEDP [41] discussed below.

One means for increasing the competitiveness of sugar production and bagasse cogeneration is by closing mills with low cane crushing capacity and integrating them into bigger adjoining mills. In 1993, there were 19 sugar mills with a cane processing rates of 55–250 t cane per hour in operation. Centralisation resulted into the closure of lower capacity crushing factories and only 6 mills remained by 2008. This was a sensitive socio-economic and political issue for the several thousands of planters and workers in the industry. During the centralisation process, several measures were adopted for workers, including offering voluntary termination of employment with an ex-gratia payment in cash and a piece of land for housing. The Government provided a blueprint (1997) to provide guidance on the closure of sugar factories. The higher crushing capacity of surviving sugar factories meant that a greater amount of bagasse was available on a single site and allowed for

the installation of larger and more efficient boilers for electricity production [37].

Energy pricing was an important factor which required government intervention to reach an agreement. The kWh price for bagasse electricity and coal was set through a PPA between the relevant parties, usually for 20 years. Following problems in agreeing the kWh bagasse price between the Independent Power Producer and CEB, the Ministry of Energy and Public Utilities, with assistance from the World Bank, conducted a study of the price setting mechanism using the cost of a diesel plant as a comparison to suggest a kWh price for electricity from coal and bagasse [36]. Different kWh prices were set for intermittent, continuous or firm power, and whether investments were made in new or second hand equipment including any change brought to existing plants. 44% of the bagasse kWh price was indexed to changes in oil prices while the other 56% was fixed for continuous electricity generation. The price for firm power was based on the plant configuration and was mainly indexed to coal price, cost of living indices in the country and the foreign exchange rate. Here, the Mauritian government played an important role in bringing actors together and brokering an agreement.

This period also saw a series of national strategic plans for the sugar sector as a whole, within which energy always featured strongly. These included the Sugar Sector Strategic Plan, the Roadmap for the Mauritius Sugarcane Industry for the 21st Century and the Multi-Annual Adaptation Strategy.

The Sugar Sector Strategic Plan (2001–2005) was aimed at sustaining the viability of the sugar industry by consolidating the reduction in cost of sugar production and generating additional income from sugarcane co-products. Several initiatives were undertaken both at field and factory level. At the factory level, it was proposed to continue the centralisation process thereby placing high priority on electricity generation in cogeneration plants. It was equally proposed to adopt energy conservation measures to reduce the internal energy consumption (both steam and electricity) in the sugar factory and the power plant in order to enable higher electricity export to the grid.

The Roadmap for the Mauritius Sugarcane Industry for the 21st Century was introduced in 2005 to enable Mauritius to preserve its sugar industry together with its many socio-economic and environmental benefits. The plan was a response to the reduction in sugar price as a result of the EU sugar regime reform. It forecasted that 1700 GWh of electricity would be sold by bagasse/coal cogeneration plants to the grid by 2015 with bagasse accounting for about 600 GWh (the estimated maximum techno-economic potential at that time). Higher biomass supply through the collection of cane tops and leaves and trash as well as the development of new varieties of ‘energy cane’ and ‘fuel cane’ with higher biomass potential was expected to reduce the use of imported coal. Optimisation of the bagasse electricity potential would be realised by: enabling state-of-the-art firm power plants to be annexed to all centralised sugar factories; emphasizing energy efficiency in all factories to reduce energy consumption; using sugarcane agricultural cane field residues as a supplementary fuel wherever possible; constructing two new plants of 82 MW and 35 MW capacity in 2007 and 2011/2012 respectively, depending on the electricity needs in the country; replacing two existing plants in 2008–2011 with roughly the same generation capacity (around 65 MW); designing all power plants to meet with applicable environment standards. Bagasse cogeneration projects could also generate income through Emission Reduction Credits which would improve the financial viability of the projects [42].

The Multi-Annual Adaptation Strategy (2005–2015) was a consolidation plan of the previous ‘Roadmap for the Mauritius Sugarcane Industry for the 21st Century’ and was designed to restructure the sugar industry to remain competitive. The focus of this plan was to set up four large sugarcane processing complexes with efficient sugar mills together with surrounding by-products plants (e.g. bagasse cogeneration plants or distilleries). The sugar mills were planned to be converted to flexible and modern facilities to produce alternative types of sugar

(raw, plantation white, refined and special sugars), to maximise electricity production in state-of-the-art cogeneration plants, and to produce bioethanol from molasses and possibly cane juice in distilleries. The full bagasse potential, estimated to be around 600 GWh annually, was to be tapped by 2015. In addition, research and development projects such as the development of energy and fuel canes and the use of sugarcane agricultural residues were predicted to more than double the power generation capacity of the sugar industry [43].

3.3.3. Niche level technical innovation and changing policies

In addition to the institutional and policy changes across the existing regime in this period scientific research and technical innovation continued apace, seeking improved energy yields and further diversification of products. Energy and fuel cane varieties were being developed: ‘Fuel cane’ was expected to contain higher fibre content in the stalk including the tops, leaves and trash and would be suitable only for energy production. ‘Energy cane’ would have adequate sucrose content to enable both sugar and energy production. Breeding programmes and experimental field trials were conducted during this period and results indicated that the fibre production per hectare for fuel cane could increase by three to four times compared to the conventional sugarcane varieties. Energy and fuel cane varieties were projected to have lower production cost than cane meant for sugar production since they would have a longer crop cycle, require less replantation and weed control, and they would be more resistant to pests, diseases and wind. Harvesting of fuel cane could also be undertaken during longer period of the year compared to existing sugarcane varieties thus reducing the idle time of harvesting equipment (Researcher 7–9 2015, pers. comm., 23 July).

3.3.4. MLP analysis of Phase 2

Phase 2 saw a ramp up in the firm power plants that use bagasse plus coal to provide power to the grid to reduce dependence on petroleum imports after a period of policy learning and adjustment. Articulation of a vision and learning processes are important success factors for developing niches under the SNM framework; the Mauritian government pursued these relentlessly throughout the 1990s and early 2000s, transforming both the power supply and sugar sectors through scaling up niche innovations originating in the 1980. The electricity supply from Independent Power Producers (mostly bagasse plus coal cogeneration plants) now accounted for around 60% of the country’s supply while the CEB produced the remaining 40%, thus the independent power plant niche of Phase 1 had become key to the regime in this phase. The significant investments previously expected to be made by the CEB in the power sector on fuel oil capacity was displaced and raised by the private sector. At the same time, reform of the EU sugar regime put downward price pressure on sugar producers in affected countries. In Mauritius, there was an industry-wide response to reduce costs led by government policy, with a series of fiscal, organisational and technology innovations introduced. This accords with the SNM approach that an integrated set of policies to address the economic, technical, social and institutional barriers to the diffusion of new technology is necessary.

3.4. Phase 3: integrated plan (2009-present)

3.4.1. Landscape level

During this phase, energy was part of a high-level political push to pursue a sustainable development model in Mauritius, driven by multiple constraints imposed on an island and global concern for climate change. This was captured in the “Maurice Ile Durable” (2013) policy. There was also increasing public awareness of environmental issues which included public opposition to the construction of a new coal-fired power plant.

Further reform of the sugar regime is set to abolish the guaranteed internal price, quotas and export limits by the end of 2017 [44]. The

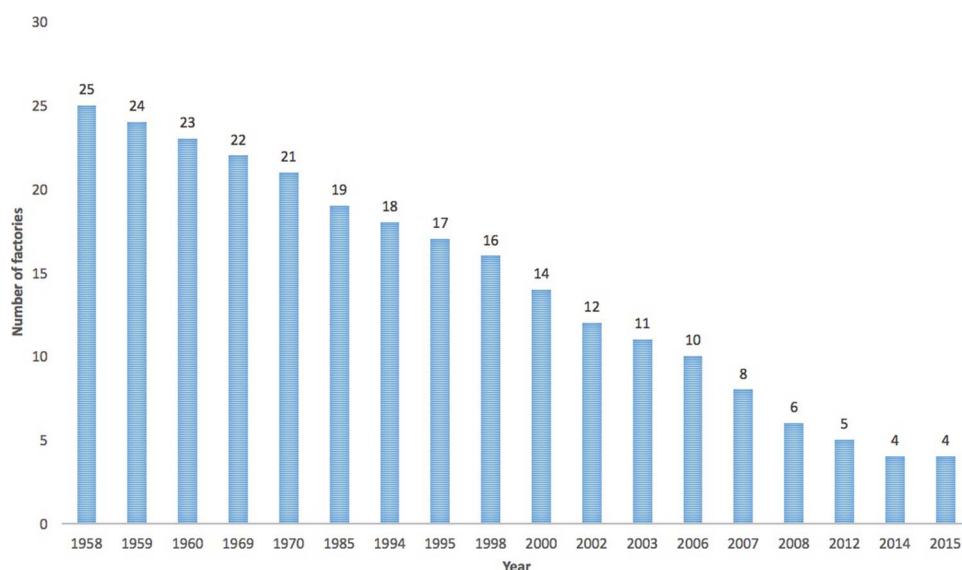


Fig. 3. Number of sugar mills in Mauritius.
Data Source: [47] MSIRI Annual reports, 1958–2015.

Mauritian sugar industry is likely to be severely impacted as it has limited alternative markets and high production costs for its sugar [45]. However, sugar now accounts for < 1% of GDP in Mauritius and many sugar businesses diversified into other industries, such as tourism, financial services and textiles. The country still has strong social and cultural ties to sugar cultivation and there is broad political support for the sugar industry.

3.4.2. Regime level

Sugarcane is currently grown on around 57,000 ha of land in Mauritius which represents around one third of the country land area or around 85% of the land used for agriculture [46]. Around 4 million tonnes of cane is produced annually which generates around 1.2 million tonnes of bagasse. The centralisation process was completed in 2014 resulting in the current four sugar factories, all of which supply electricity to the grid. The centralisation process is illustrated in Fig. 3. The total installed capacity for bagasse/coal power generation is 240 MW which accounts for about 30% of the country's installed capacity [7]. Around 510 GWh of bagasse electricity was generated in 2015 with around 381 GWh sold to the grid [7].

The government set a target of 35% renewable electricity generation share by 2025 (Table 1) in the Long-Term Energy Strategy (LTES) 2009–2025 [48] and reiterated its commitment in the 'Maurice Ile Durable (MID)' (2013). These strategies underpin the countrywide sustainable development framework. Energy production in the sugar industry, in particular bagasse cogeneration, is expected to contribute 17% to the country's electricity supply by 2025 (around 50% of the

renewable energy supply in the country). This figure excludes the potential of sugarcane agricultural residues or the emergence of energy and fuel canes (see below). These plans consolidate the policies and strategies proposed in the MAAS for the sugar industry. They not only highlight the energy supply potential of the sugar industry but the linked cross-cutting issues to agricultural development (dominated by the sugar industry in the country), environmental protection (GHG emissions, land preservation and green landscape) and socio-economic development (sustainable livelihoods and multiple economic benefits).

3.4.3. Niche level technical innovation and changing policies

3.4.3.1. Developments in biomass fuels. Several niche level technical innovations have emerged in Phase 3 in response to changes at the landscape and regime levels. Alternatives were sought to boost electricity production while limiting the use of coal. These innovations include the use of sugarcane agricultural residues (SAR), continued development of energy and fuel cane varieties, and combustion of new biomass crops in cogeneration plants.

Sugarcane agricultural residues (SAR) are cane tops and leaves and trash left in sugarcane fields after harvest of millable cane for sugar production. SAR provides promising potential for boosting electricity production from sugarcane given that it can be independently combusted or co-fired with bagasse in existing bagasse cogeneration plants. Combustion of SAR has been of key interest in several cane producing countries in particular in Brazil [49–52]. In Mauritius, Deepchand [53] first investigated and experimented with the combustion of SAR which was further consolidated with successive research and development attempts. Seebaluck and Seeruttun [54] found that the optimal mix for existing cogeneration plants in Mauritius was 70% bagasse and 30% SAR. This option would require the collection of 35% of SAR and would increase the amount of electricity produced by about 37% per tonne of cane. SAR would incur additional costs for collection, handling, transportation and pre-processing to make the material compatible with existing cogeneration plants. However, it is projected to generate electricity at competitive cost compared to other sources of energy. The production of electricity from SAR would also lead to a CO₂ emission saving of around 560 kg of CO₂ per tonne cane [54] as the cane residues would be combusted in an efficient way rather than burnt in the cane fields after harvesting. Such work had been emphasized in the MAAS 2006–2015 sugar industry strategy and the LTES 2009–2025 national energy strategy. In 2016, a bagasse/coal cogeneration plant in Mauritius burnt mixtures of bagasse and SAR to establish the technically feasible production mix including commercial costs implications with a view to enhance informed negotiations between the electricity supplier

Table 1
Forecasted electricity generation mix 2010–2025.
Source: LTES 2009–2025 [48].

| Fuel Source | | Percentage of Total Electricity Generation | | | |
|------------------|------------------|--|------------|------------|------------|
| | | 2010 | 2015 | 2020 | 2025 |
| Renewable | Solar PV | 0% | 1% | 1% | 2% |
| | Wind | 0% | 2% | 6% | 8% |
| | Hydro | 4% | 3% | 3% | 2% |
| | Bagasse | 16% | 13% | 14% | 17% |
| | Waste to energy | 0% | 5% | 4% | 4% |
| | Geothermal | 0% | 0% | 0% | 2% |
| Sub-total | | 20% | 24% | 28% | 35% |
| Non-Renewable | Coal | 43% | 45% | 44% | 40% |
| | Fuel Oil | 37% | 31% | 28% | 25% |
| | Sub-total | 80% | 76% | 72% | 65% |

and the utility.

Another key development was that research on energy and fuel cane undertaken in Mauritius in the past two decades has led to the development of several varieties for fuel cane, currently under field trials (this was one of the main focal points in the previous period). Research in Barbados has yielded promising results which showed that the fibre percentage in cane could be increase by up to about 25% [55]. However, research conducted in South Africa showed that transfer of research findings to commercial scale application can be challenging [56]. As such further research is required to replicate the experimental outcomes in the fields and any transfer and adaptation of these new varieties to other regions would take several years [57].

A further innovation was the development of energy crops suitable for abandoned agricultural lands. Despite the many reforms undertaken in the sugar industry in Mauritius, around 25% of cane lands have been abandoned over the past two decades. These lands were mainly marginal areas and those of the small planter's community which could not modernise agricultural operations due to the dispersed and small nature of their plots. The amount of cane produced (and subsequently bagasse) decreased over the years thus lowering the electricity generation potential and renewable energy contribution to the country. However, the change in land use with the availability of thousands of hectares of land for alternative use provides opportunities for biofuels crop production. The economic return from these lands could thus be safeguarded or even improved to provide sustainable livelihoods for the many planters and operators in this sector (Manager 13 2015, pers. comm., 23 July).

The Government of Mauritius in its 'Budget 2014' proposed the introduction of a 'Biomass Development Scheme' under the Maurice Ile Durable Fund which aims to produce efficient bioenergy crops for small planters [58]. 'Arundo Donax' is proposed under the scheme to produce a feedstock that could substitute for coal for power generation in existing cogeneration plants. Agricultural field trials of the crop have been undertaken since 2011 to establish the crop yield and energetic potential [59] and in 2016 the crop was harvested and combusted successfully in an existing cogeneration plant. The agricultural production cost, supply chain cost and production cost have also been determined [60]. The developments are very promising, but this niche innovation faces some opposition from planters and sugar companies due to the long history of sugar cultivation in Mauritius. The knowledge base for growing other crops is not as large and Mauritian culture is closely tied to cultivation of sugar (Manager 13 2015, pers. comm. 27 July).

3.4.3.2. Developments in plant equipment. Two key technical innovations within cogeneration plants have emerged. The first is the use of higher boiler pressures in cogeneration plants enable higher electricity productivity due to greater efficiency in the turbines. Thus, higher pressure and temperature configurations are key factors for increasing exportable surplus electricity.

The modern bagasse/coal cogeneration plants in Mauritius use high pressure boiler configuration of 81 bar while those in India use up to 87 bar. The boiler pressure can be increased to 115 bar, but this requires higher investment, improved water treatment and process control technologies (Manager 1 2015, pers. comm., 15 July). Following the termination of the Power Purchase Agreement (PPA) of an existing bagasse/coal power plant in Mauritius, a new plant is being proposed that would operate at 90 bar boiler configuration (the highest in the country). This development is highly relevant for the construction of other new bagasse power plants in Mauritius and globally.

The second major innovation is the development of a carbon burnout facility. The operation of bagasse/coal cogeneration plants involves the processing of around 660,000 t of coal annually. Compared to bagasse combustion, coal burning results in significantly higher amount of coal ash (around 14% of the coal mass). This needs to be disposed of properly on a small island where there is competition for land use and the only landfill site will reach saturation by 2021. Coal ash from existing power plants contains between 15 and 30% of

unburnt carbon which could be combusted to generate more heat [61].

One of the bagasse/coal plants is currently constructing a carbon burnout facility which would operate a fluidized bed boiler configuration to burn the coal ash (reducing the unburnt carbon content to below 6%) and to generate low pressure steam for use in the sugarcane processing complex [62]. The processed ash could then be used in the construction industry as a component in cement/concrete [61]. Development of this construction material is ongoing.

3.4.3.3. Growing expertise and overseas investment. As the Mauritian economy comes under strain from the anticipated sugar price fall, sugar companies are increasingly looking to expand into other countries. This could lead to expansion of cogeneration in sub-Saharan Africa, including transfer of old sugar mills and cogeneration plants overseas. The three largest sugar companies in Mauritius already own sugar mills in other African countries where opportunities for selling electricity to the grid is being explored (Manager 2 & 3 2015, Pers. Comm., 16 July). Mauritius faces competition from investors from outside the region, such as from Brazil, who are increasing their involvement in energy from sugarcane in Africa but are more interested in realising the potential for liquid biofuels rather than electricity generation [63].

Mauritian companies are also growing in technical capabilities in designing and operating cogeneration plants. The relationship with foreign operation companies is likely to change in the future (Manager 1 2015, pers. comm., 15 July).

3.4.4. MLP analysis of Phase 3

In this phase, feeding power to the grid from cogeneration plants using sugarcane bagasse had become part of the regime, but further technical innovations to improve the efficiency and financial viability were added. Spurred by Landscape pressures from broadening international attention to climate change action and sustainable development lead to political commitment to sustainable development as articulated through the Maurice Ile Durable policy at the Regime level. This renewed the articulation of the government's vision of bagasse cogeneration as part of the future energy mix in Mauritius. A decline in the economic significance of sugar itself, with entrenchment of co-generated electricity as a crucial element of power supply supported completion of the sugar plant centralisation, in turn supporting continued modernisation of plants. Ambitious targets for rising shares of renewable energy drive innovation, research and trials for new crop types, and new means of extracting ever-greater value from the crop. Exploration of these technologies began in previous periods, but economic and political imperatives were insufficient for these niche innovations to challenge the incumbent industry at the time. Similarly, the motivation for continued innovation in cogeneration technology, notably higher boiler pressures has grown, and coalesced with ambitions for overseas investments.

Challenges still remain. Within the current regime, financial relationships between small planters and sugar mills or cogeneration plants may be holding up developments towards beneficial crop types. The reduction in sugar price has placed financial pressure on small planters who cannot modernise agricultural production due to the smallness of their sugarcane plots. Planters are currently paid for the sugar content of the cane: given the multiple revenue sources from sugarcane (sugar recovery and electricity production), a better formula could be developed for compensating crop planters based on both the sugar as well as the fibre content of cane. This would provide them with an incentive to switch to growing varieties better suited to the changing sector, such as fuel cane varieties.

4. Discussion and conclusions

This is a study on the development of cogeneration in Mauritius, intended to be useful for illuminating pathways for future industrial development for other African countries and possibly beyond. The main

drivers for successful cogeneration in Mauritius were concerns over dependence on fossil fuels in the electricity sector, downward price pressure from the reform of the EU sugar regime in the sugar sector, as well as rising demands for (clean) electricity. Mauritius has responded to these landscape pressures through a succession of niche innovations which have gradually been adopted into the regime level and led to the successful scale up of grid-connected bagasse cogeneration. Regulatory change allowing the formation of independent power producers, centralisation of sugar mills to ensure adequate availability of bagasse to annexed cogeneration plants, the use of a complementary fuel (coal) in the off-crop season to provide firm base load electricity to the grid and precise financial incentives have all been instrumental. The case study provides a clear example of the progression of a technical innovation from early stage through to commercial deployment and then sector-wide scale up, over the course of several decades, and the use of the MLP to identify the factors shaping this trajectory.

The Mauritian case also identifies the important role of targeted and responsive policy packages, sustained over a long period, for the successful scale up of niche innovations. Initially policies were targeted at supporting the innovations directly, but as the narrative for the second phase shows, key to scaling up was the set of regulatory changes and policies made to “destabilise” the existing regime by making space in the power sector regime for the firm bagasse/coal generation. These findings lend support to Kivimaa and Kern’s [27] argument that policy attention should be directed at both the niche and the regime levels.

This case study also offers new insights into the dynamics between technical and policy innovations, and between niches and regimes, in a developing economy context. Ratinen and Lund [29] argue that high degrees of inclusion in policy process and policy outcomes lead to substantial sociotechnical changes. The collaborations between government and industry in both strategy development and implementation are evident throughout the periods analysed. However, the success in Mauritius was dependent in large part on it being a developmental state [64,33] and on the highly-regulated nature of the sugar market globally. The three classic success factors for niche development (articulation of a vision, building social networks and learning processes) are largely taken up by the closely connected government and industrial sectors. The Mauritian Government managed though to maintain sufficient elements of competition and market forces to incentivise productivity and innovation.

Beyond these structural conditions, the case shows that Mauritius could respond quickly to innovations and barriers to technical developments in a strategic way due to the relative abundance of finance, technical expertise and strong governance structures. The strong social and cultural ties to sugar production continue to enable niche innovations in the sugar industry while other developments are concurrently being explored in the agriculture and wider energy sectors (including solar PV, wind, waste-to-energy). Some developing countries with an existing sugar industry, such as Vietnam, could increase the contribution of electricity from bagasse by improving plant efficiency and adopting policy lessons from Mauritius to encourage sugar mills to feed in to the grid as independent power producers [65]. However, some countries will have to overcome significant institutional and market barriers to do so. For example, in Malawi the technology in the sugar mills is dated, access to finance is difficult, power purchase agreements have not been successfully negotiated with the utility and ownership of the sugar business is dominated by foreign investors [66]. Moreover, even in this conducive environment the transition from small scale cogeneration serving factory needs to modern cogeneration as a major national renewable energy source in Mauritius has taken more than three decades.

4.1. Further research

There has been little work done to date on incorporating policy analysis into the MLP for developing countries in different situations.

More research is needed to illuminate the mechanisms by which policy innovations influence changes at the regime and niche levels in a developmental state. These future mechanisms need to be considered under different institutional environments, levels of capacity and development models.

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